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Axial Length Changes with Shifts of Gaze Direction in Myopes and Emmetropes

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ABSTRACT

PURPOSE: To investigate the changes in axial length occurring with shifts in gaze direction.

METHODS: Axial length measurements were obtained from the left eye of 30 young adults (10 emmetropes, 10 low myopes and 10 moderate myopes) through a rotating prism with 15° deviation, along the foveal axis, using a non-contact optical biometer in each of the nine different cardinal directions of gaze over 5 minutes. The subject's fellow eye fixated on an external distance (6m) target to control accommodation, also with 15° deviation. Axial length measurements were also performed in 15° and 25° downward gaze with the biometer inclined on a tilting table, allowing gaze shifts to be achieved with either full head turn but no eye turn, or full eye turn with no head turn.

RESULTS: There was a significant influence of gaze angle and time on axial length (both $p < 0.001$), with the greatest axial elongation ($+18 \pm 8 \mu\text{m}$) occurring with infero-nasal gaze ($p < 0.001$) and a slight decrease in axial length in superior gaze ($-12 \pm 17 \mu\text{m}$) compared with primary gaze ($p < 0.001$). In downward gaze, a significant axial elongation occurred when eye turn was used ($p < 0.001$), but not when head turn was used to shift gaze ($p > 0.05$).

CONCLUSIONS: The angle of gaze has a small but significant short-term effect on axial length, with greatest elongation occurring in infero-nasal gaze. The elongation of the eye appears to be due to the influence of the extraocular muscles, in particular the oblique muscles.

INTRODUCTION

Myopia is the most common refractive error in the younger population¹⁻⁴ and is characterized by an axial elongation of the eye over time.⁵⁻⁷ The prevalence of myopia has been documented to be increasing over recent years in certain populations.^{1, 8-10} A range of hypotheses has been proposed to explain the mechanism of myopia development, and although both genetic and environmental factors are thought to be involved, the exact cause of the axial elongation of the eye underlying myopia is still unknown.

Near work is one previously documented environmental risk factor for myopia. A number of previous studies have noted significant associations between performing near work activities and the development¹¹⁻¹⁵ and progression of myopia.¹⁶ A number of occupational groups that typically undertake intense near activities such as textile workers^{17, 18} and microscopists^{19, 20} have also been found to have an increased prevalence of myopia. The ocular changes that typically accompany near work in order to maintain clear single vision, include contraction of the ciliary muscle to alter accommodation, and changes in extraocular muscle (EOM) tension to alter gaze direction (near work typically involves convergence, but can also often involve other shifts in gaze direction such as downward gaze). The documented association between near work and myopia have prompted a variety of previous studies to examine whether accommodation or convergence lead to significant changes in the axial length of the eye.

A number of recent studies has documented a small, but statistically significant transient axial elongation of the eye associated with short term accommodation and

this is assumed to be due to the mechanical force caused by ciliary muscle contraction.²¹⁻²⁴ It has also been hypothesized that the mechanical forces generated by the extraocular muscles during convergence may be a factor in the axial elongation associated with myopia development.^{25, 26} Using ultrasound biometry to measure axial length, Bayramlar et al²⁶ suggested that convergence may lead to a significant increase in axial length, as axial elongation was found to occur with near fixation under cycloplegia (i.e. with accommodation paralysed, but active convergence). However, Read et al²⁷ using partial coherence interferometry, did not find any significant changes in axial length of the eye during convergence in the horizontal plane. The influence of the changes in EOM tension associated with other directions of gaze (e.g. downward gaze), aside from convergence, upon the eye's axial length have not been investigated.

Given that near work typically involves accommodation, convergence and downward gaze, we were interested to investigate the influence of the EOMs on the axial length of the eye in different directions of gaze. We have therefore measured the changes in axial length and choroidal thickness occurring following shifts in gaze in each of the nine cardinal directions of gaze.

METHODS

Subjects

Thirty young adult subjects aged between 18 and 30 years (mean age of 23 ± 3 years) were recruited for this study. All subjects were free of any significant ocular or

oculomotor diseases or dysfunction and had no history of eye surgery. Subjects who habitually wore soft contact lenses ($n = 12$) were asked to abstain from lens wear for 2 days prior to and during the study. Approval was obtained from the University Human Research Ethics Committee prior to the commencement of the study. Subjects were treated in accordance with the Declaration of Helsinki and gave written informed consent before participating. Before testing, subjects were screened for their eligibility for the study. Ocular history, high contrast visual acuity, non-cycloplegic subjective refraction and a series of clinical accommodation and binocular vision measures were recorded for each subject. All subjects exhibited monocular amplitude of accommodation greater than 7 D. No subjects with any binocular abnormalities (e.g. significant esophoria or exophoria or poor near point of convergence), strabismus (e.g. horizontal or vertical heterotropia), amblyopia or ocular motility disorders were included in this study. All subjects had best corrected visual acuity of logMAR 0.00 or better in both eyes. Subjects were classified based upon their spherical equivalent refraction as either emmetropes ($n = 10$, spherical equivalent ranging from +0.25 to -0.50 DS, mean -0.31 ± 0.16 DS), low myopes ($n = 10$, spherical equivalent -0.75 to -2.75 DS, mean -1.73 ± 0.53 DS) or moderate myopes ($n = 10$, spherical equivalent -3.00 to -6.00 DS, mean -4.40 ± 1.30 DS). None of the subjects had anisometropia greater than 1.00 DS or astigmatism greater than 1.50 DC. Our subjects exhibited a range of ethnic backgrounds, being either Caucasian (total $n = 13$; 3 emmetropes, 4 low myopes and 6 moderate myopes), East Asian (total $n = 12$; 4 emmetropes, 4 low myopes and 4 moderate myopes), or Indian (total $n = 5$; 3 emmetropes and 2 low myopes).

Experimental design and data collection procedures

All axial length measurements in this study were taken from each subject's left eye, along the foveal axis, using a non-contact optical biometer (Lenstar LS 900, Haag-Streit International, Koeniz, Switzerland) based upon the principle of optical low coherence reflectometry. The Lenstar provides highly precise measurements of ocular biometrics that are comparable with other validated instruments.^{28, 29} At each measurement session, 5 repeated biometry measurements were collected on each subject. The experimental sessions for all subjects began at approximately the same time of day (between 9 am and 10 am), to minimise the potential confounding of results by diurnal variations in axial length.³⁰

Measurements of axial length in cardinal gaze directions

To allow biometry measures to be collected along the foveal axis in different directions of gaze, identical rotating prisms were mounted before each eye in front of the biometer (Figure 1). The prisms were 15° deviation, wedge prisms with a broadband anti-reflection coating for near infrared wavelengths ranging from 650-1050 μm (Thorlabs, USA). The prisms were rotated so that the subject could fixate the instrument's internal fixation target in eight cardinal gaze directions (no prism was used in primary gaze) with a 15° deviation for both eyes, while biometry measures were collected.

Subjects were given their vertex distance corrected, full distance spherical equivalent refractive error correction in a trial lens mounted in front of the fellow (right) eye during each of the testing conditions. The subject's fellow eye was therefore viewing

a free space, high contrast, Maltese cross target at 6 m distance with an accommodation demand of 0 D through the trial lens. Therefore, in dichoptic view, an image of the Maltese cross was visible from the right eye and an image of the biometer's fixation target was simultaneously seen from the left (tested) eye (Figure 1).

Initially, each subject performed a distance primary gaze viewing task (such as watching a DVD) binocularly at a 6 m distance for 5 mins to provide a “wash-out” period for prior visual tasks. Then we measured (baseline) axial length using the biometer in primary gaze. This baseline measurement was taken prior to each session for all cardinal gaze measurements. The subject's axial length and ocular biometrics were measured in each of the nine cardinal directions of gaze:

1. Primary gaze: no prism
2. 15° Abduction: prism base in (nasal)
3. 15° Adduction: prism base out (temporal)
4. 15° Elevation: prism base down
5. 15° Depression: prism base up
6. 15° Dextro-elevation: prism base infero-temporal
7. 15° Dextro-depression: prism base supero-temporal
8. 15° Levo-elevation: prism base infero-nasal
9. 15° Levo-depression: prism base supero-nasal

For each gaze direction, the subject was asked to fixate on the centre of the external Maltese cross target (0 D accommodation) displayed on a TV screen viewed through the wedge prism with the fellow right eye. The external target's position was adjusted (horizontally and vertically) until the centre of the Maltese cross coincided with the

image of the biometer's fixation target seen with the left eye. Throughout the experiment, subjects were advised to maintain dichoptic superimposition of the Maltese cross (right eye) and biometer's fixation target (left eye) and to advise if there was any loss of focus on the cross or drift in the superimposition of the targets. Measurements of axial length and ocular biometrics were then collected after 0 min (immediately after shifting gaze direction to fixate the target) and 5 mins from this starting time (continuously viewing the Maltese cross target). A break (5 mins) was given after each trial to avoid carry over effects between the consecutive gaze measurements. During this period, the subject watched TV at a 6 m distance. In pilot studies, we observed that any changes in axial length that occurred with changes in gaze direction were fully recovered within 2-3 minutes after shifting gaze from oblique back to primary gaze. The order of testing the gaze conditions was also randomized to avoid the potential for systematic bias in the results.

Measurements of axial length in downward gaze using a tilting stage

To validate the measurements taken through the prisms and to further study the relative influence of gravitational effects and EOM forces on the axial length changes in downward gaze, axial length measures were also collected with the biometer inclined at 15° and 25° on a tilting stage (i.e. without the use of any prisms). Measurements of axial length were again performed over 5 mins under two different test conditions with the subject either looking down with their head inclined downward, or again looking down with the head remaining in the upright position (eye gaze downward). For the first condition, the subject's head was tilted in downward gaze at an angle equal to the instrument axis (15° or 25°). This ensured

that the shift in gaze was achieved through a head turn, with no turn of their eyes (Figure 2 A and Figure 2 C) and reflected the effect of gravity on biometric changes in the eye without eye turn. For the second condition, the subjects' head position was adjusted to maintain an upright head position (primary gaze) using a custom made head rest. In this condition, the subject had to turn their eyes only (with no head turn) to 25 degrees and 15 degrees downward gaze, under the actions of the EOMs, to fixate on the instrument's target (Figure 2 B and Figure 2 D). To verify the head angles during downward and primary gaze, we captured digital images of the head positions for both gaze conditions for all subjects. The digital image of the head's profile allowed us to fit a "reference line" to the facial features (i.e. a straight line connecting the top of the ear to the bottom of the nose) to confirm the relative head angle in downward gaze compared to the primary gaze condition. The relative head angles based on analysis of these digital images were $13.9 \pm 3.6^\circ$, $0.7 \pm 2.9^\circ$, $24.1 \pm 3.4^\circ$ and $2.9 \pm 3.8^\circ$ for the testing conditions of 15° head turn only (no eye turn), 15° eye turn alone (no head turn), 25° head turn only (no eye turn) and 25° eye turn alone (no head turn) respectively.

Data analysis

Axial length (AxL, the distance from the anterior corneal surface to the retinal pigment epithelium) measurements for each gaze direction were taken from the biometer's data output. Choroidal thickness (ChT) was derived through the manual measurement of the distance from the retinal pigment epithelium (peak P3) to the choroid/sclera interface (peak P4) in the biometer's A-scan data originating from the posterior eye. The methods of measurement of ChT from the Lenstar A-scan data is

explained in detail elsewhere.^{31,32} ChT measures from the Lenstar instrument have previously been found to exhibit a strong correlation and reasonable agreement with ChT measures obtained from spectral domain optical coherence tomography (SD OCT).³² In order to avoid bias, a masked observer performed the manual analyses of the distance from P3 to P4 peaks to determine ChT.

Although the subject's accommodation was relaxed with a distance viewing target during the experiment, some small changes in lens thickness did occur in various gaze directions that could potentially cause errors in AxL measures. To account for any small errors in axial length induced by lens thickness changes, we used the formula outlined by Atchison and Smith,³³ to calculate a corrected AxL measurement at every gaze direction for each subject. For example, the anterior chamber depth decreased by a mean $21 \pm 22 \mu\text{m}$ and lens thickness increased by a mean $19 \pm 35 \mu\text{m}$ in infero-nasal gaze and this led to a group mean adjustment in axial length of $1.13 \pm 1.63 \mu\text{m}$. All AxL measurements presented in this paper therefore represent the AxL corrected for each subject's individual changes in lens thickness during each gaze condition.

A repeated measures analysis of variance (ANOVA) was performed to assess the significance of changes in ocular biometrics, AxL and ChT changes in the various conditions (within-subjects factors) including gaze angle and the effect of measurement time (0 and 5 mins) within the task, effect of head positions (head turn versus eye turn), and the effect of angle of the eye turn (15° inferior gaze versus 25° inferior gaze). The between-subjects factor was refractive error group (emmetropes, low myopes and moderate myopes).

Validation of AxL measurements through the wedge prism

Before testing, we verified the accuracy of the axial length measures with the presence of the prism. The axial length of a spherical model eye was measured with the biometer using the conventional technique. Then, we repeated these measurements (three times) in the presence of the 15° prism. There was no significant difference in the measured length of the model eye, with and without the prism in place (mean difference 0 ± 0 micron). Moreover, we also found a significant correlation in the measured length of the same human eyes ($n = 30$) for the inferior gaze direction (depression) with base up prism (mean \pm SD: 24.469 ± 0.970 mm) and without prism (looking down without head turn) using the tilting stage (24.466 ± 0.969 mm) (Pearson's $R^2 = 0.99$, $p < 0.001$). These results suggest the use of the 15° prism did not introduce any substantial error in the measurements.

RESULTS

Angle of gaze

Significant changes in AxL were observed as a function of angle of gaze ($p < 0.001$) (Figure 3). Changes in AxL also exhibited a significant effect of time (repeated measures ANOVA, $p = 0.004$) and gaze by time interactions ($p < 0.001$). Considering each individual direction of gaze, AxL was significantly elongated in infero-nasal gaze (mean change from baseline $+11 \pm 9$ μ m at 0 min, $+18 \pm 8$ μ m at 5 mins, pairwise comparison, both $p < 0.001$), inferior gaze (mean change from baseline $+9 \pm 9$ μ m at 0 min, $+15 \pm 10$ μ m at 5 mins, both $p < 0.001$) and in supero-nasal gaze

(mean change from baseline $+10 \pm 7 \mu\text{m}$ at 0 min, $+15 \pm 10 \mu\text{m}$ at 5 mins, both $p < 0.001$). AxL was found to decrease significantly in superior (mean change from baseline $-10 \pm 17 \mu\text{m}$ at 0 min, $p = 0.003$ and $-12 \pm 17 \mu\text{m}$ at 5 mins, $p < 0.001$) and supero-temporal (mean change from baseline $-8 \pm 8 \mu\text{m}$ at 0 min, $p = 0.003$ and $-11 \pm 9 \mu\text{m}$ at 5 mins, both $p = 0.001$) gaze directions. Primary, nasal, temporal and infero-temporal gaze results all showed no significant change in axial length, compared to baseline ($p > 0.05$).

There were no significant differences ($p > 0.05$) in the baseline AxL measurements between any of the directions of gaze (baseline measurements were obtained prior to each session for all cardinal gaze measurements after 5 mins of viewing a far target). For example, the difference between primary gaze baseline and inferior gaze baseline measurements of the axial length was less than 3 microns. The use of repeated baseline measures ensured that there was minimal risk of cross over effects between any two consecutive gaze direction measurements.

The mean AxL for all subjects was $24.457 \pm 0.969 \text{ mm}$, and the mean AxL of myopic subjects (low myopes $24.443 \pm 0.783 \text{ mm}$ and moderate myopes $25.204 \pm 0.697 \text{ mm}$) was significantly greater than the emmetropes (mean $23.724 \pm 0.844 \text{ mm}$) ($p < 0.001$). Axial elongation in the infero-nasal gaze direction over time was significantly greater ($p < 0.001$) in moderate myopes (mean change from baseline $+17 \pm 10 \mu\text{m}$ at 0 min, $+25 \pm 6 \mu\text{m}$ at 5 min) compared to low myopes (mean change from baseline $+7 \pm 4 \mu\text{m}$ at 0 min, $+12 \pm 4 \mu\text{m}$ at 5 mins) and emmetropes (mean change from baseline $+8 \pm 7 \mu\text{m}$ at 0 min, $+13 \pm 6 \mu\text{m}$ at 5 mins). Subjects with longer eyes (greater axial length) exhibited a greater tendency for axial elongation in the infero-

nasal direction after the 5 mins task (Pearson's $R^2 = 0.52$, $p < 0.001$). We also found a significant correlation between refractive error (spherical equivalent refraction) and the mean change in AxL in the infero-nasal gaze direction after 5 mins of the task (Pearson's $R^2 = 0.71$, $p < 0.001$), indicating a greater tendency for axial elongation in infero-nasal gaze over time for the subjects with a higher refractive error (Figure 4). The changes in AxL also approached significance for the time by refractive error interaction ($p = 0.05$, repeated measures ANOVA), suggesting differences in the onset and amplitude of AxL change in myopic and emmetropic subjects over the 5 mins near task.

We excluded ChT data for six subjects (2 emmetropes, 2 low myopes and 2 moderate myopes) due to inconsistent P4 choroidal peaks. Therefore, the ChT analyses represent data from 24 subjects. The choroid was typically found to change in the opposite direction to the AxL change (Table 1). However, unlike the AxL change, there were no significant variations in ChT with respect to the gaze (angle $p = 0.30$), time ($p = 0.09$) and gaze by time ($p = 0.45$) factors. The mean amplitude of changes in ChT from baseline with gaze directions were not significantly different between the myopic and emmetropic subjects ($p = 0.83$).

Changes in AxL and ChT in inferior gaze (head turn vs. eye turn)

Similar to the results with the 15° rotary prisms, AxL increased significantly in inferior gaze over time with eye turn (no head turn) from primary gaze (mean difference $+7 \pm 11 \mu\text{m}$ at 0 min, $+14 \pm 11 \mu\text{m}$ at 5 mins with 15° angle and mean difference $+9 \pm 13 \mu\text{m}$ at 0 min, $+15 \pm 15 \mu\text{m}$ at 5 mins with 25° angle) (Figure 5). ChT decreased

significantly in inferior gaze with eye turn (no head turn) from primary gaze (mean difference $-7 \pm 4 \mu\text{m}$ at 5 mins with 15° angle and mean difference $-7 \pm 5 \mu\text{m}$ at 5 mins with 25° angle) ($p < 0.05$) (Figure 5). However, there were no significant changes in AxL or ChT in inferior gaze with head turn (no eye turn) (Figure 5). We observed almost equal magnitude of change in AxL in downward gaze with 15° and 25° angles (mean difference less than 2 microns, $p > 0.05$).

DISCUSSION

This study demonstrates that small but significant changes in AxL occur in five of the eight gaze directions, compared to primary gaze. The AxL changes observed appear to be due to the influence of the EOMs with change in gaze direction, since the effect was eliminated when head turn was used instead of eye turn, to shift the direction of gaze. A significant axial elongation occurred in infero-nasal gaze, supero-nasal and inferior gaze directions, with the largest magnitude of elongation found in the infero-nasal gaze direction. The primary EOMs involved in infero-nasal, supero-nasal and inferior gaze are the superior oblique, inferior oblique and inferior rectus muscles respectively.³⁴ The oblique muscles (superior oblique and inferior oblique) insert into the posterior sclera and the inferior rectus inserts into the anterior sclera.³⁵ A small decrease in AxL was found in the superior and supero-temporal gaze directions, in which the primary muscle involved in these gaze shifts is the superior rectus.³⁴ Our findings suggest that the changes in EOM forces brought about by sustained versional eye movements for 5 mins, are sufficient to alter the eye's AxL.

Greene²⁵ theorized that the oblique muscles, because of their attachment locations at the posterior globe nearer to the optic nerve head, may have the capacity to produce local stress on the posterior globe, which may cause axial elongation associated with increased vitreous pressure. The changes we observed in the AxL of the eye in the field of action of the superior oblique and inferior oblique muscles gives some support for this hypothesis. However, our data only highlight the changes in the central AxL of the eye. It would, therefore, be useful to measure changes in AxL at various locations across the retina during shifts in gaze to determine the effects of the EOMs forces on the peripheral contour of the globe.

In contrast to the AxL changes we found in the vertical and oblique gaze directions, we did not find any significant changes in AxL in nasal and temporal directions under the actions of horizontal rectus muscles (medial rectus and lateral rectus). This finding is consistent with the results of a previous study that observed little change (less than 5 microns) in the AxL of young adults both during and immediately after 15 mins of sustained convergence with 10° deviation in the horizontal gaze direction.²⁷ In contrast, Bayramlar et al²⁶ observed substantially larger changes in AxL with a greater amount of convergence (20 cm target distance) with and without cycloplegia in adolescents. Therefore, we cannot discount the possibility that larger magnitudes of convergence (> 15°) for longer periods, or a sustained convergence, could potentially cause changes in AxL.

Analysis of the effects of refractive error in our subjects, showed a significant association between the magnitude of myopic refractive error and the amount of axial elongation occurring in infero-nasal gaze. There is evidence of an overall

thinning, localized ectasia and altered biomechanical properties in the sclera of highly myopic eyes.^{36, 37} Therefore, the same force applied on the myopic sclera may cause a greater stretch compared with shorter emmetropic eyes. Studies examining the scleral biomechanical properties of animal models have found that the magnitude of scleral deformation increases over time if a constant pressure is applied to the globe.³⁸⁻⁴¹ Similarly, we observed that changes in AxL typically increased over time (up to 5 mins) when a constant external pressure was applied to the globe by the EOMs, with a fixed direction of gaze. The differences we have noted between myopic and emmetropic subjects in terms of the axial elongation of the eye with infero-nasal gaze over time may therefore reflect differences in the structural and mechanical properties of the sclera associated with myopia.

The changes we have observed in axial length were small and reflect the short term influence of shifts in gaze direction on the length of the eye. Further research is therefore required to understand the implications of these short term findings for the longer term development and progression of myopia. However, our findings of a significant axial elongation of the eye associated with inferior and inferior nasal gaze leave open the possibility that longer periods, or the cumulative effects of multiple short periods of near work activities employing downward gaze (e.g. reading in downward gaze, or microscopy) over time could potentially promote a longer term elongation of the eye and the development of myopia through the mechanical influence of the EOMs. Recent biomechanical in vitro and modelling studies suggest that fibrous tissues exist in a preferred state of mechanical equilibrium, and that adaptations (such as growth and remodelling of the tissue at the microscopic level) occur in response to changes in the mechanical environment in order to restore the

tissue's preferred mechanical state.⁴² These microscopic tissue adaptations in response to mechanical stress in ocular fibrous tissues such as the sclera could potentially result in tissue elongation.⁴³ Scleral adaptation, in response to prolonged mechanical stress from extraocular muscle force could therefore be a potential mechanism underlying myopic ocular elongation.

Other than the external forces from the EOMs, the eye's internal pressure (IOP) may also influence the AxL in different directions of gaze. Relatively small, short term elevations in IOP can lead to measurable increases in the axial length of young adult subjects.⁴⁴ Previous studies⁴⁵⁻⁴⁷ found a gaze-dependent increase in IOP, particularly in vertical gaze, resulting from contraction of the EOMs. In the future, it would be of interest to also measure the changes in IOP in the cardinal gaze directions under the actions of EOMs.

Unlike the changes in AxL, the changes in choroid were smaller, less reliable (greater standard deviations) and for most gaze directions, not statistically significant. The exact mechanism underlying the small significant changes in the choroid for the downward gaze measurements are not clear, however we hypothesise that forces from the EOMs could be transmitted from the sclera to the choroid, and thus may lead to a change in ChT, or if the EOMs are causing IOP to rise in certain gaze angles, this may apply outward pressure to the choroid.

In summary, our study suggests that the eye's axial length increases in inferior gaze directions (inferior and infero-nasal) and in supero-nasal gaze. In contrast, axial length decreases slightly in the upward directions of gaze (superior and supero-

temporal gaze). The changes in axial length appear to be due to the influence of the extraocular muscles, since the effect was eliminated when head turn was used instead of eye turn, to shift the direction of gaze.

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FIGURE LEGENDS

FIGURE 1: A schematic diagram of the experimental set-up using rotary prisms that allows ocular biometry along the foveal axis to be performed in different gaze directions with no accommodation under binocular fixation.

FIGURE 2: Subject's head postures during axial length measurement with the optical biometer using a tilting stage for various testing conditions, 15° head turn only (A), 15° eye turn only (B), 25° head turn only (C) and 25° eye turn only (D). Dashed line indicates the reference line used to determine the change in head turn angle in each condition.

FIGURE 3: The group mean changes in axial length (AxL) ($n = 30$) of the left eye (OS) in nine cardinal gaze directions with respect to baseline over 5 mins duration. Prior to each gaze measurements, the baseline value was taken after 5 mins of viewing a 6m target [i.e., no accommodation (0 D)] in primary gaze. Values at 0 min of the task were taken immediately after the task commenced. AxL values are corrected for individual subjects based on the changes in ACD and LT. In this plot, AxL changes significantly in the inferior, superior, infero-nasal, supero-nasal and supero-temporal directions from baseline over time, compared to the primary gaze (ANOVA, $p < 0.05$). Error bars represent standard error of the mean. Asterisks indicate the angles of gaze in which significant changes in axial length were found compared to baseline values ($p < 0.05$).

FIGURE 4: Changes in axial length in the left eye (OS) in infero-nasal gaze after 5 mins of the task with respect to baseline with no accommodation versus the subjects' mean spherical refractive error. The baseline value was taken after 5 mins of viewing a 6 meters target [i.e., no accommodation (0 D)] in primary gaze.

FIGURE 5: Group mean changes in axial length (AxL) and choroidal thickness (ChT) of the left eye in 15° and 25° downward gaze with either head turn only (i.e., head-down and eyes straight) or with eye turn only (i.e., head straight and eyes rotate down) with respect to baseline (with no accommodation) over the 5 mins task for the

subset of 24 subjects with reliable choroidal thickness data. Prior to each test condition, the baseline value was taken after 5 mins of viewing a 6m target [i.e., no accommodation (0 D)] in primary gaze. In this plot, AxL and ChT change significantly in both 15° and 25° downward gaze directions with eye turn (ANOVA, $p < 0.05$). However, AxL and ChT shows no significant changes in downward gaze with head turn (both 15° and 25°) (ANOVA, $p > 0.05$).

Table 1. Group mean (\pm SD) changes of axial length (AxL) and choroidal thickness (ChT) in the left eye (OS) in nine cardinal gaze directions [primary (P), supero-temporal (ST), superior (S), supero-nasal (SN), nasal (N), infero-nasal (IN), inferior (I), infero-temporal (IT) and temporal (T)] with respect to the baseline condition over 5 mins. Prior to each gaze measurements, the baseline value was taken after 5 mins of viewing a 6 m target [i.e. no accommodation (0 D)] in primary gaze. Values at 0 min of the task were taken immediately after the gaze direction commenced. Positive values indicate an increase in AxL and ChT. Bold numbers indicate values where the changes from baseline of AxL or ChT in different gaze directions are statistically significant ($p < 0.05$).

	Mean \pm SD changes from baseline (primary gaze) [microns]			
	AxL (n =30)		ChT (n = 24)	
Gaze	0 min	5 mins	0 min	5 mins
P	-1 \pm 5	+1 \pm 4	+1 \pm 8	-1 \pm 9
ST	-8 \pm 8	-11 \pm 9	+1 \pm 10	-2 \pm 14
S	-10 \pm 17	-12 \pm 17	-1 \pm 12	-3 \pm 13
SN	+10 \pm 7	+15 \pm 10	-6 \pm 12	-8 \pm 16
N	-1 \pm 6	+2 \pm 7	-5 \pm 9	-5 \pm 16
IN	+11 \pm 9	+18 \pm 8	-4 \pm 9	-11 \pm 22
I	+9 \pm 9	+15 \pm 10	-6 \pm 13	-10 \pm 17
IT	-1 \pm 7	-1 \pm 7	-5 \pm 18	-2 \pm 18
T	-2 \pm 6	-3 \pm 10	+1 \pm 7	-1 \pm 11

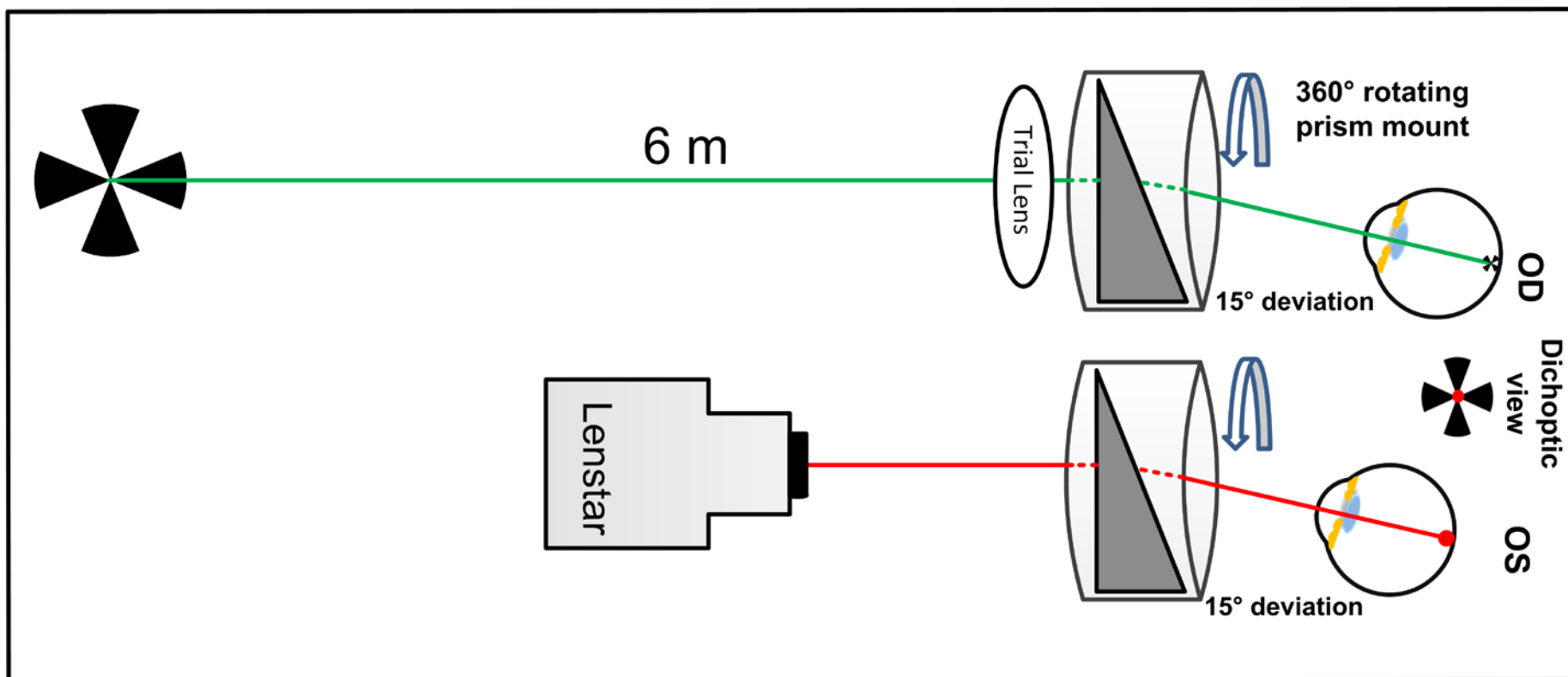
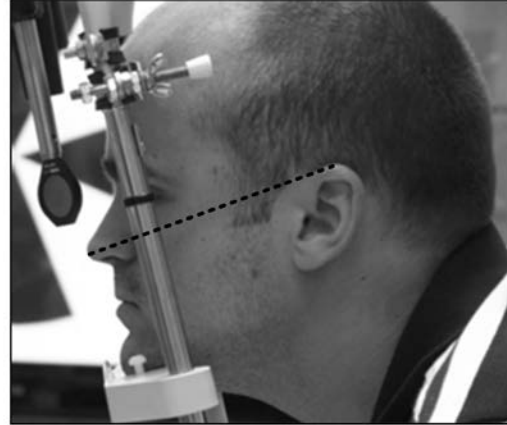


FIGURE 1

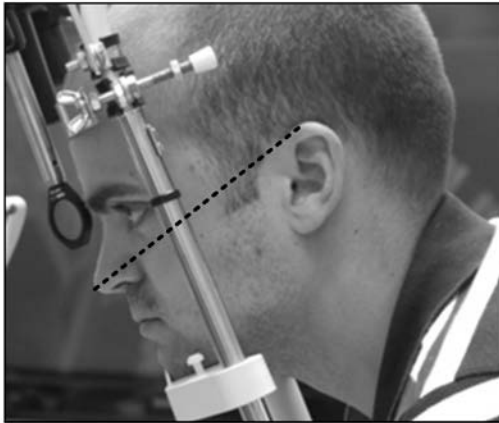
A. 15° Head turn only



B. 15° eye turn alone



C. 25° Head turn only



D. 25° eye turn alone

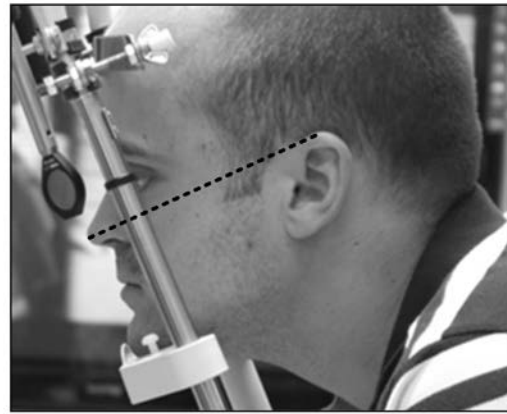


FIGURE 2

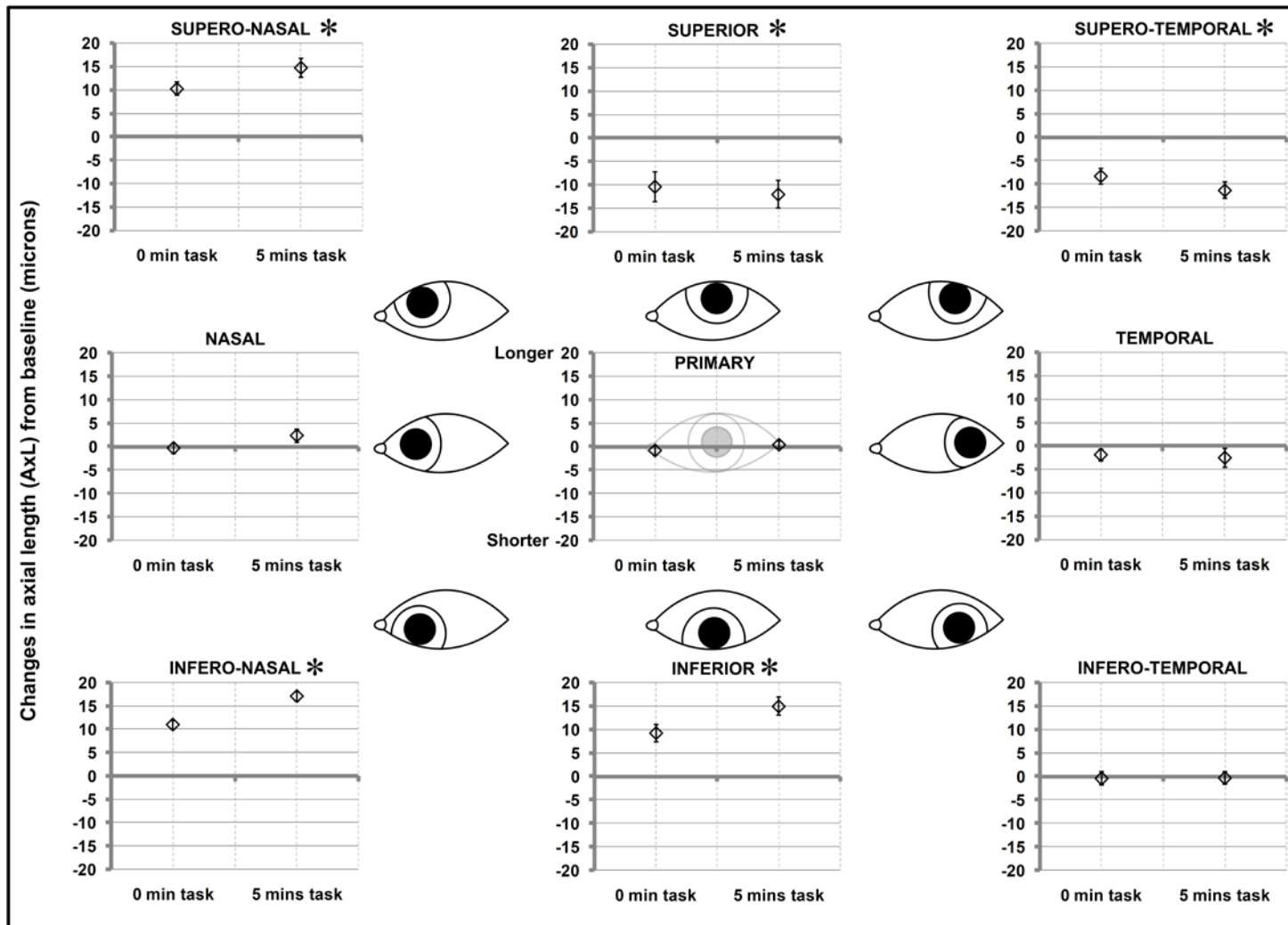


FIGURE 3

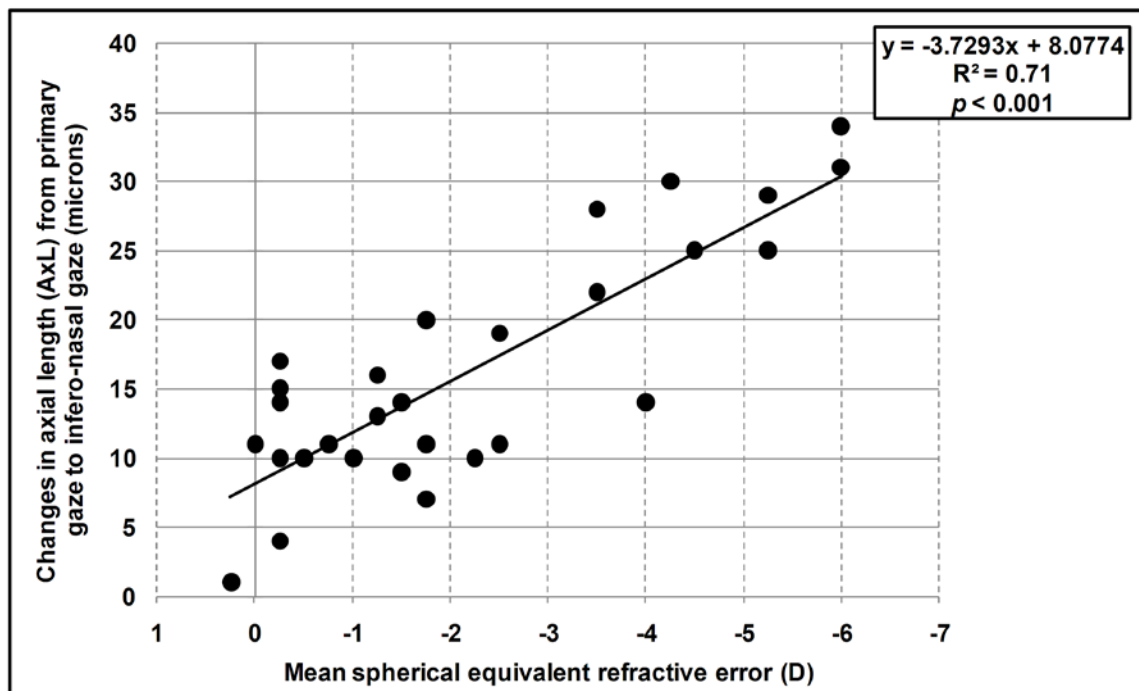


FIGURE 4

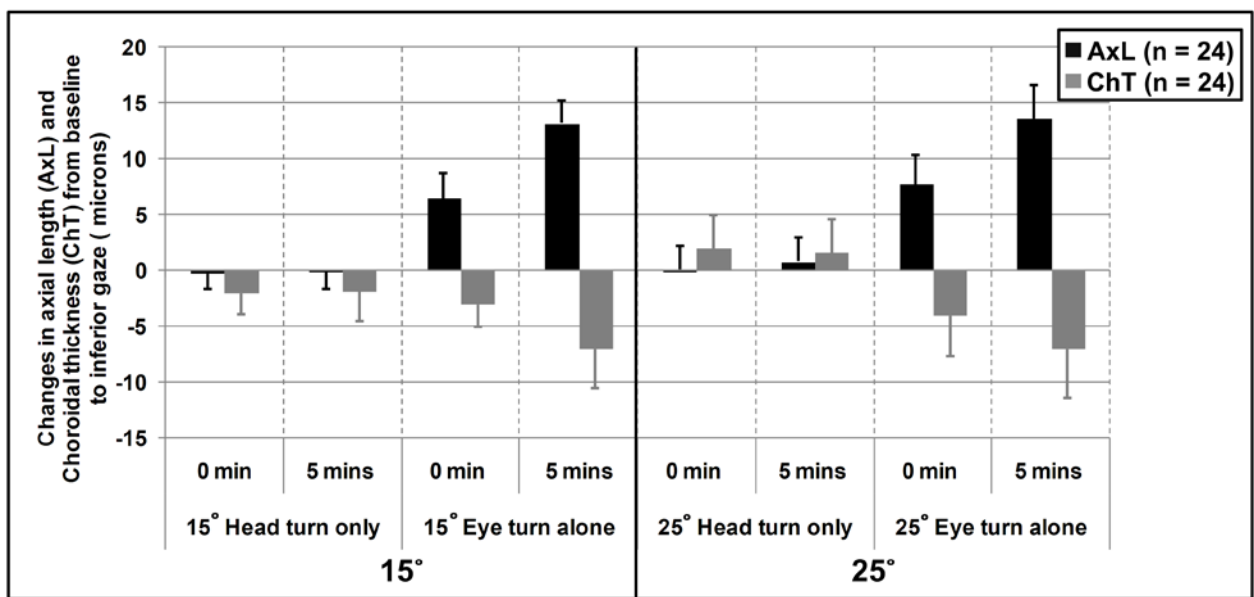


FIGURE 5